Report for 2005SD38B: Fate of Disinfectants and Disinfection By-Products in Water Distribution Systems

Publications

- There are no reported publications resulting from this project.

Report Follows

State Water Resources Institute Program (SWRIP)
March 2005 to February 2006

PART I.

Title: Fate of Disinfectants and Disinfection By-Products in Water Distribution Systems

Research Category: Engineering

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Descriptors: disinfection by-products, water distribution, Stage 2 D/DBP Rule,

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Problem Statement and Objectives:

Chemical disinfectants are dosed to water supplies to kill pathogenic organisms and provide a protective residual in the distribution system. The chlorine, chloramine and/or chlorine dioxide residuals decay in the distribution system through volatile escape, autodecomposition, or reaction with reducing agents such as metal pipe or organic matter. The residual disinfectants may react with organic matter to produce trihalomethanes (THMs) and haloacetic acids (HAAs). THMs and HAAs are potential carcinogens, and thus are regulated at the state and federal level under the Disinfectant/Disinfectant by-Product (D/DBP) Rule. Under the current rule, all water systems using a disinfectant sample for D/DBPs at locations representing the average and maximum residence times in the distribution system. These locations are chosen by the systems based upon known water use patterns and (primarily) distance from the water treatment plant. Annual average DBP concentrations are compared against the maximum contaminant level (MCL) to determine compliance with the Rule.

The next phase of D/DBP rule (Stage 2 D/DPB) will require systems to systematically determine the locations of the highest THM and HAA concentrations in the distribution system and sample at those locations to determine compliance with the MCL. As a result of this new approach, some South Dakota systems currently in compliance with the D/DBP Rule will likely exceed the MCL. Additionally, there are virtually no published reports relating distribution system characteristics, disinfectant types, and disinfectant residual concentrations to THM and HAA concentrations in South Dakota systems. Lacking these resources, South Dakota systems have little site-specific guidance for choosing sample locations for compliance with the Stage 2 D/DBP rule.

This project provides information that helps identify relationships between disinfection practices (distribution system characteristics, disinfectant types, and disinfectant residual concentrations) and THM and HAA concentrations in South Dakota systems. This knowledge will enable the systems to choose appropriate sample locations for the Stage 2 D/DBP rule and premeditate compliance issues, thus avoiding real costs and customer backlash associated with non-compliance with drinking water regulations.

The results will also be very helpful to primacy agencies as they work with systems to implement the Stage 2 D/DBP rule. The magnitude of system compliance efforts are a function of water source and population served by the system. Smaller systems are often required to sample less frequently and at fewer locations, requiring even greater wisdom in choosing appropriate sample locations.

South Dakota water systems use chloramine, free chlorine and chlorine dioxide as chemical disinfectants. They distribute water into systems of PVC and ductile iron pipes arranged in looped (municipal) and extensively branched (rural water) networks, containing storage tanks and booster disinfection systems. These system characteristics, along with water age and temperature, are primary factors affecting disinfectant residual decay and disinfection by-product (DBP) formation in these

systems. While trihalomethanes (THMs) have been shown to increase with water age, haloacetic acids (HAAs) have been found to increase to a point in the distribution system, but then decrease, especially in areas of low disinfectant residual. Since water quality tends to have characteristics related to the hydrogeology of the water source, DBP formation in distribution systems tends to be region-specific.

The objectives of this project are to more fully understand the behavior of chlorine and disinfection by-products in distribution systems in the upper great plains region, and develop correlations between the characteristics of distribution systems and chlorine decay and DBP production. Results of the project can be used by water systems to assess the locations where water samples should be collected that will provide the maximum DBP concentration as required by the proposed Stage 2 Disinfectant/Disinfection By-Product Rule.

The project was accomplished by obtaining characteristic data from 4 water distribution systems in South Dakota that represent a range of disinfectant types, system size, and pipe materials. Correlations developed from the characteristic data were used select locations where additional samples should be collected to provide missing data regarding DBP formation. Samples collected at these locations were analyzed for DBP concentrations, the results of which were then correlated with system characteristics to develop relationships that can extend to other distribution systems.

Related Research:

The principal investigator has recently completed several studies in this region related to water treatment and distribution, the results of which provide background for this project. One such study (Cami 2003) used a hydraulic model to model chlorine/chloramine decay and DBP formation in a large rural water system in western South Dakota. However, lack of field data from the system prevented rigorous calibration of the model and prevented further applications of the knowledge gained from the study. Additionally, the impacts of disinfectants and oxidants on treated water quality have been studied at water plants treating the Missouri River (DeBoer 2003) and the Big Sioux River (Baumberger and DeBoer 2003). The three studies mentioned above all lacked full-scale distribution system data to enable correlation between water quality and system characteristics. This proposed project would provide data needed to close the gap between knowledge of system characteristics and knowledge of water quality in this region.

The principal investigator is not aware of other similar studies in this region that have been reported in the literature. However, several studies of distribution system water quality modeling (Gallard and von Gunten 2000, Vandermeyden and Hartman 2001), distribution system hydraulic modeling (DiGiano and Carter 2001), full-scale distribution system water quality (Hatcher et al. 2004), and pilot-scale distribution system water quality (Baribeau et al. 2000, Taylor et al. 2003) have been reported. The results of these studies provide correlations between system characteristics and water quality that form a basis for comparison with the results of this project. However, the results of the this study are specific to distribution systems in the upper great plains, and provide region-specific information that is generally lacking in the literature.

Methods and Procedures:

South Dakota water distribution systems were solicited to participate in this research study. The systems were selected to represent systems most significantly affected by the Stage 2 D/DBP Rule. The four South Dakota distribution systems that volunteered to be a part in the study included Sioux Falls, Watertown, Randall Community Water District (RCWD), and Mid Dakota Rural Water System (Mid Dakota). Sioux Falls and Watertown represent municipal systems that utilize a blend of ground water and surface water. Mid-Dakota and RCWD represent rural systems that utilize surface water sources. Sioux Falls and Mid-Dakota presently use chloramine as a secondary disinfectant; however, Sioux Falls used free chlorine prior to 2001. Watertown and RCWD utilize free chlorine as a secondary disinfectant. Thus, the systems provided the range of information that would characterize systems most impacted by the Stage 2 Rule.

Historical data that was requested and obtained from these systems included: disinfectant use (type, concentration), source water characteristics, chlorine residual concentrations, TTHM/HAA5 concentrations, temperature, flow, and any additional information deemed helpful to the study. Hydraulic models of the systems were reviewed when available. Some of the systems provided more information than others due to greater sampling obligations for the Stage 1 D/DBP Rule. Information was also obtained from the South Dakota Department of Environment and Natural Resources (SDDENR) as well as from volunteering consecutive systems.

ESRI ArcGIS 9.0® and Microsoft Excel® were used to analyze the factors affecting DBP formation in South Dakota systems. The main factors analyzed include: disinfectant residual type and concentration, temperature, and relative water age. ESRI ArcGIS 9.0® was utilized to provide a statistically based, visual representation of the spatially and temporally varied disinfectant residuals in each system. Data were also analyzed using Microsoft Excel® and correlations were made relating the aforementioned factors to DBP formation. Once trends had been established, maximum TTHM/HAA5 locations were predicted and two rounds of TTHM/HAA5 sampling were scheduled for the months of highest and lowest temperature. This is a similar procedure as would be followed for systems developing an Initial Distribution System Evaluation (IDSE) required by the Stage 2 D/DBP Rule. Field sampling was scheduled and completed in three of the four distribution systems. The samples were collected in August, 2005 and March, 2006.

Results and Discussion:

Factors that typically influence DBP formation include disinfectant type, disinfectant dose, source water quality and bromide content, temperature, water age, pH, pipe type and wall environment, and distribution system layout (Adams 2005, Carlson and Hardy 1998, Clark and Sivaganesan 1998, EPA 2003, Liang and Singer 2003). Based on historical data from water systems examined in this study, the main factors influencing DBP formation in South Dakota appear to be residual disinfectant type, temperature, and water age. It will be important for water distribution systems to analyze these three factors in order to accurately develop their IDSE. Additional factors certainly have a potential to effect DBP formation in these systems but were not extensively researched in this study. This is either because the factors were held relatively constant and thus would not contribute to DBP concentration and disinfectant residual variations, or they were not factors that water distribution systems could easily use to predict peak THM and HAA5 locations for their IDSE. They were and should, however, be considered and will thus be mentioned in the results and discussion.

Residual Disinfectant Literature has shown that chemical disinfectants can react with the natural organic matter (NOM) present in water to form DBPs (Adams et al. 2005, Carlson and Hardy 1998, Speight and Singer 2005). Studies have also shown that there are correlations that can be made relating disinfectant residual characteristics and behavior with DBP formation in water distribution systems (Clark and Sivaganesan 1998, Speight and Singer 2005). The DBP concentrations in the four South Dakota systems were shown to be notably affected by residual disinfectant type, concentration, and behavior. Residual disinfectant and DBPs were correlated in these systems.

Residual Behavior Watertown and RCWD use chlorine (free chlorine) as a secondary disinfectant. Mid-Dakota uses chloramine as a secondary disinfectant. Sioux Falls switched from free chlorine to chloramine as the secondary disinfectant in 2001 and thus contributed chlorine data prior to June of 2001 and chloramine data thereafter. The disinfectant changeover in Sioux Fallswas very beneficial for the purpose of comparing the behavior of the two residual types, and, consequently, Sioux Falls data were frequently used as the basis for comparison to the other systems. Based on the data provided by these systems, chloraminated systems yielded more stable and persistent disinfectant residuals throughout the distribution systems. Results from the systems using free chlorine were found to be less stable and less persistent. Figure 1 illustrates the relative variations of disinfectant residuals throughout the distribution systems using chloramine and free chlorine as secondary disinfectants.

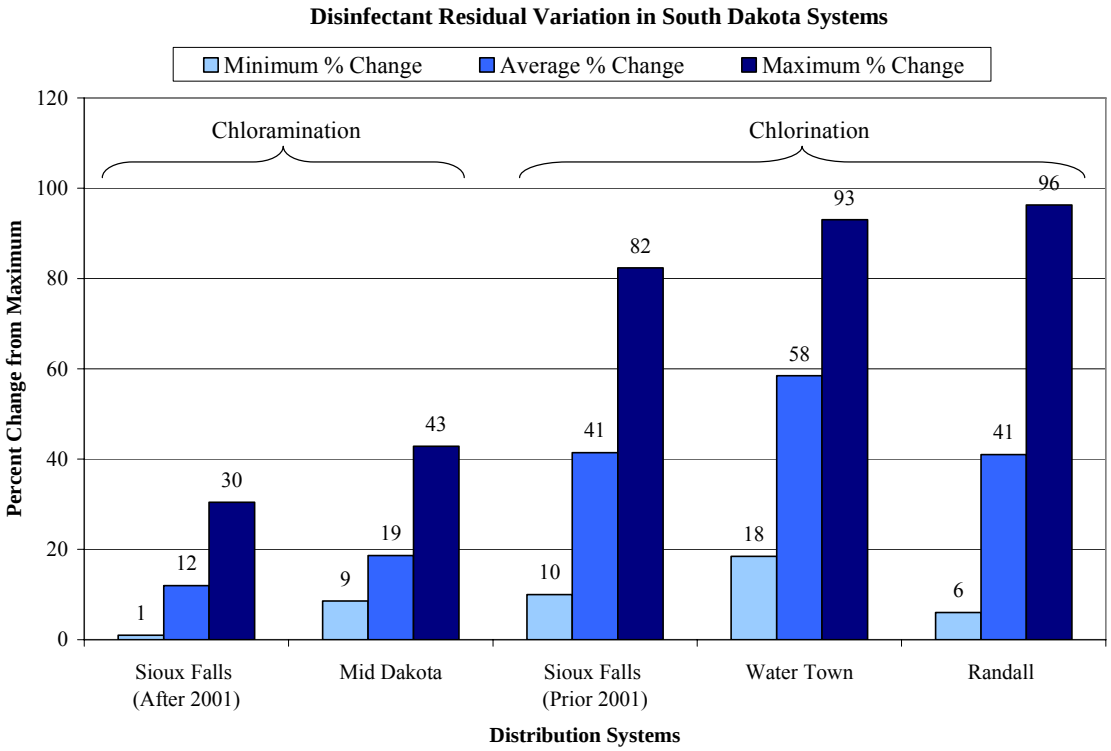

Figure 1. A comparison of disinfectant residual persistence and stability for four water systems

Figure 1 shows that the systems utilizing chlorine exhibited percent differences across their systems ranging from 6 to 96 percent while the systems utilizing chloramine had percent differences across the system ranging from 1 to 43 percent. The lower percent difference across the systems indicates that chloramine exhibits a higher stability and more persistent residual than does free chlorine. These results agree with studies reported in literature that found chloramine residuals were consistently more stable across a distribution system (Norton and LeChevallier 1997, Sung et al. 2005).

The spatial analysis features of ESRI ArcGIS 9.0® were used to envision residual dose and behavior across the distribution systems. Kriging was used to estimate chlorine residual concentrations where field sample data were not available, enabling development of maps showing chlorine residual contours across the distribution system. These maps were developed on quarterly intervals using historical data, with selected months also being representative of temperature variation and water usage. Figure 2 illustrates the variation of chlorine residual across the Sioux Falls water distribution system in February 2001, ranging between 1 and 2.5 mg/L. The brown (darker) color represents higher chlorine residual concentrations, and the lighter (yellowish) color represents lower chlorine residual concentrations. In comparison, Figure 3 shows the variation of a chloramine residual for the city of Sioux Falls, South Dakota in February of 2002. The consistent brown color in Figure 3 exemplifies the conclusion that chloramine is a more persistent residual than is chlorine and indicates the residuals are at a higher concentration than when free chlorine is used as the secondary disinfectant. Relative to implementing the Stage 2 D/DBP Rule, these results infer systems utilizing free chlorine will likely have good potential to create correlations between chlorine residual and DBP formation, since greater residual decay occurs across the system. On the other hand, systems utilizing chloramine as a secondary

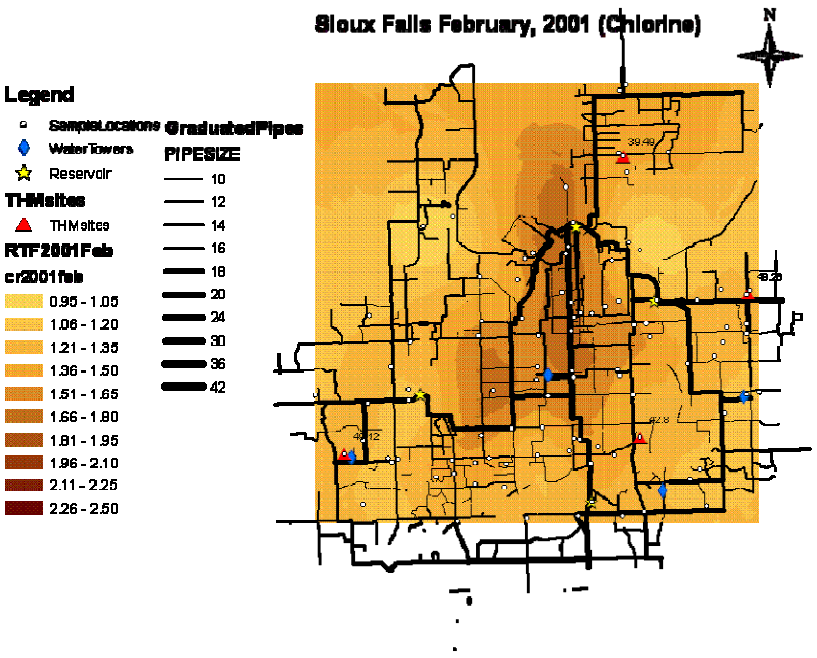

Figure 2. Chlorine residuals present in the Sioux Falls water distribution system (February 2001).

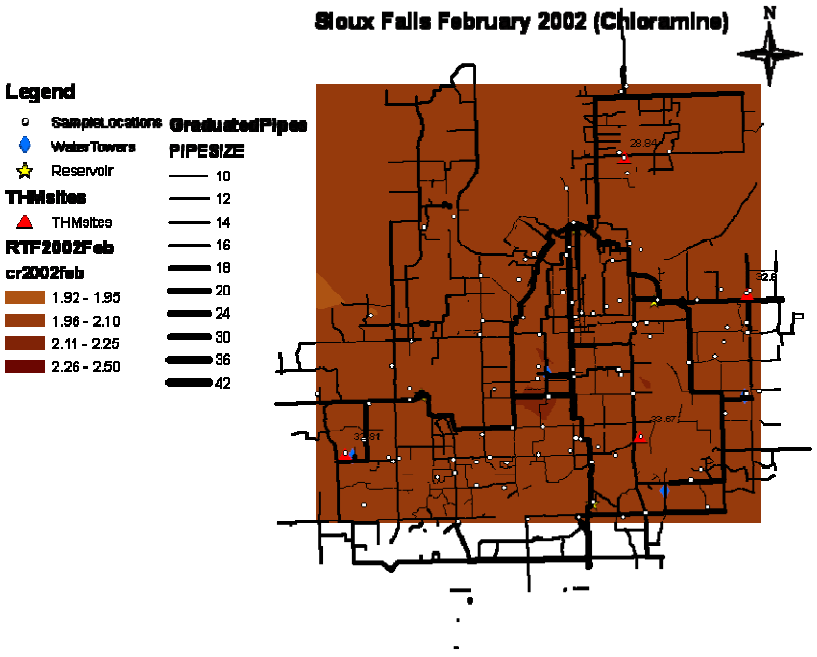

Figure 3. Chloramine Residuals present in the Sioux Falls water distribution system (February 2002).

disinfectant will experience greater difficulty creating reliable correlations, since the residual disinfectant residual concentrations exhibit little variation across the distribution system.

Residual Type-Impact on DBPs Free chlorine reacts with NOM in the water to form DBPs at a faster rate then does chloramine. The DBP data collected and analyzed for the South Dakota systems exhibited this quality. Generally, the systems utilizing chlorine had higher THM/HAA values then the systems using chloramine. The data in Table 1 indicate higher THM/HAA5 concentrations in systems utilizing free chlorine as a disinfectant residual rather than chloramine.

Table 1. Ranges of THM/HAA5 concentrations for four South Dakota water distribution systems

	CHLORINATION		CHLORAMINATION	
	THM	HAA	THM	HAA
Water System	**mg/l**	**mg/l**	**mg/l**	**mg/l**
Sioux Falls	29 -140	9.4-52	20-59	6.8-27
Watertown	25.8-142	4.5-128		
Mid Dakota			17.8-57	8.6-46.4
RCWD	30.2-100	4.5-91		

Sioux Falls provides an excellent example of the impact of disinfectant residual type on DBP formation. Figure 4 illustrates the behavior THM and disinfectant residual levels over time in Sioux Falls.

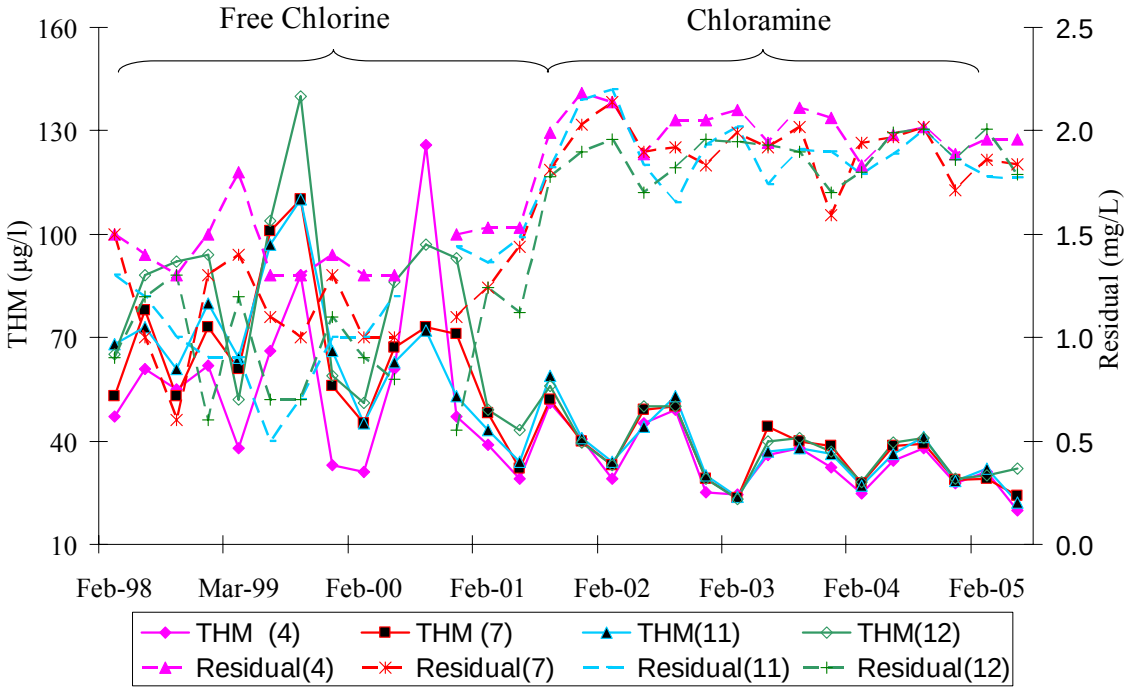

Figure 4. Sioux Falls historical THM concentrations and disinfectant residual concentrations. (Numeric values 4, 7, 11, and 12 represent different sample locations.)

Sioux Falls initiated secondary disinfection with chloramine residual in 2001. From Figure 4, one can see how the chlorine residuals and THM concentrations varied widely when free chlorine disinfection was utilized. THM concentrations are elevated and at times exceeded regulatory MCLs, although the

system was always in compliance with the pertinent MCLs when the annual average concentrations were calculated for compliance. After switching to chloramine as a secondary disinfectant, THM concentrations decreased markedly and were more uniform across the distribution system. Chlorine residual concentrations increased and were more consistent. Data from other water distribution systems in South Dakota yielded similar relationships between disinfectant type and DBP production. Acknowledging the other possible affecting factors that could skew observable correlations, it is also evident that the other systems utilizing free chlorine resulted in higher overall THM/HAA5 values than did systems utilizing chloramine (see Table 1).

Residual Concentration-Impact on DBPs Studies have shown that the relative concentrations of DBPs increase with decreasing disinfectant residual creating an inverse relationship between residual disinfectant concentration and DBP formation (Clark et al. 1998, Gang et al. 2002). This is apparent in South Dakota systems utilizing either free chlorine or chloramine although the chloramine concentration exhibited lower impact on DBP formation than free chlorine. Figure 5 illustrates the inverse correlation between TTHM and chlorine residual for RCWD.

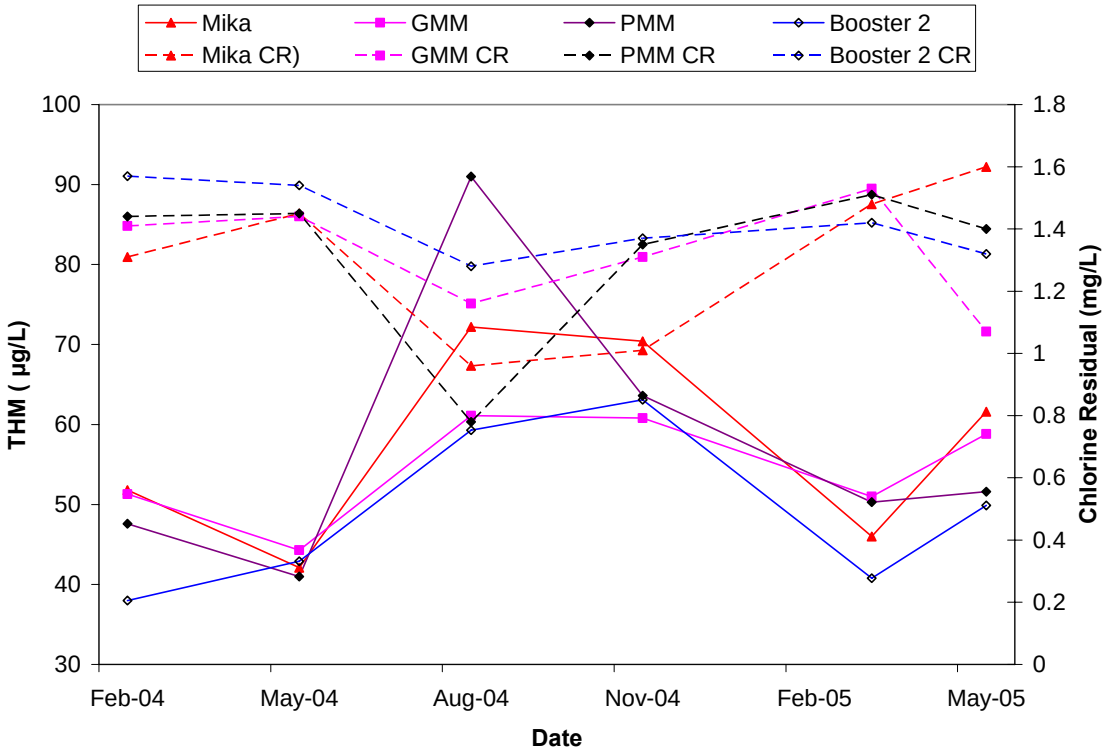

Figure 5. Free Chlorine residual and the TTHM concentration with respect to the date. Mica, GMM, PMM, and Booster 2 represents different sample locations.

In Figure 5, one can see that the peaks in TTHMs typically occur at periods of lower chlorine residuals. Similar analysis of the four South Dakota systems produced comparable results. Figure 5 also shows the peak TTHM concentration occurred in the month of August which will support a subsequent conclusion that temperature is also an important factor affecting the formation of DBPs.

While TTHMs have been found to form directly from the consumption of chlorine (Clark and Sivaganesan 1998, Pereira et al. 2004), HAAs have been found to increase to a point in a distribution system and then decrease due mainly to biological activity and chemical degradation of one of the forms of HAA (trichloroacetic acid) to TTHM. HAAs have been found to degrade when the disinfectant

residual decays to a concentration of approximately 0.5 mg/l or less (Chen and Weisel 1998). This effect was observed in the Watertown Lake Plant HAA data on a few occasions.

In regard to the impact on IDSE implementation, based on the South Dakota systems reviewed in this study, systems would typically find highest THMs in areas of lowest free chlorine or chloramine residual. In areas where the free chlorine residual drops below 0.5 mg/L, HAA5s may decrease through degredation, and thus the highest HAA5s would be found in the distribution system adjacent to the low chlorine residual location. Systems in South Dakota using chloramine as a secondary disinfectant would typically experience very low variation in DBP concentrations (both TTHM and HAA5) and low variation in chlorine residuals as well. In chloraminating systems, the maximum TTHM and HAA5 concentrations both would likely exist at the maximum residence time in the system.

Temperature Research has shown that DBP concentration and rate of formation tends to increase with increases in temperature (Clark and Sivaganesan 1998). A study by Chen and Weisel (1998) found that TTHM concentrations in summer were almost double the concentrations in winter but found that HAA5s did not exhibit a statistically significant increase in concentration in summer versus winter. They also found that the reaction rate of DBPs increases with increase in temperature - the higher temperature in the warm season accelerates the rate of DBPs production in the distribution system as compared to the cold season. Temperature variations occur more predominantly in surface waters rather than ground waters. Lastly, temperature effects are more typically pronounced in systems utilizing free chlorine rather than chloramine.

Temperature appeared to have a direct affect on the formation of DBPs in South Dakota systems. In the four systems examined in this study, DBP concentrations were higher in the summer than in the winter. Figure 6 shows the effect of temperature on the formation of DBPs in RCWD, a system using

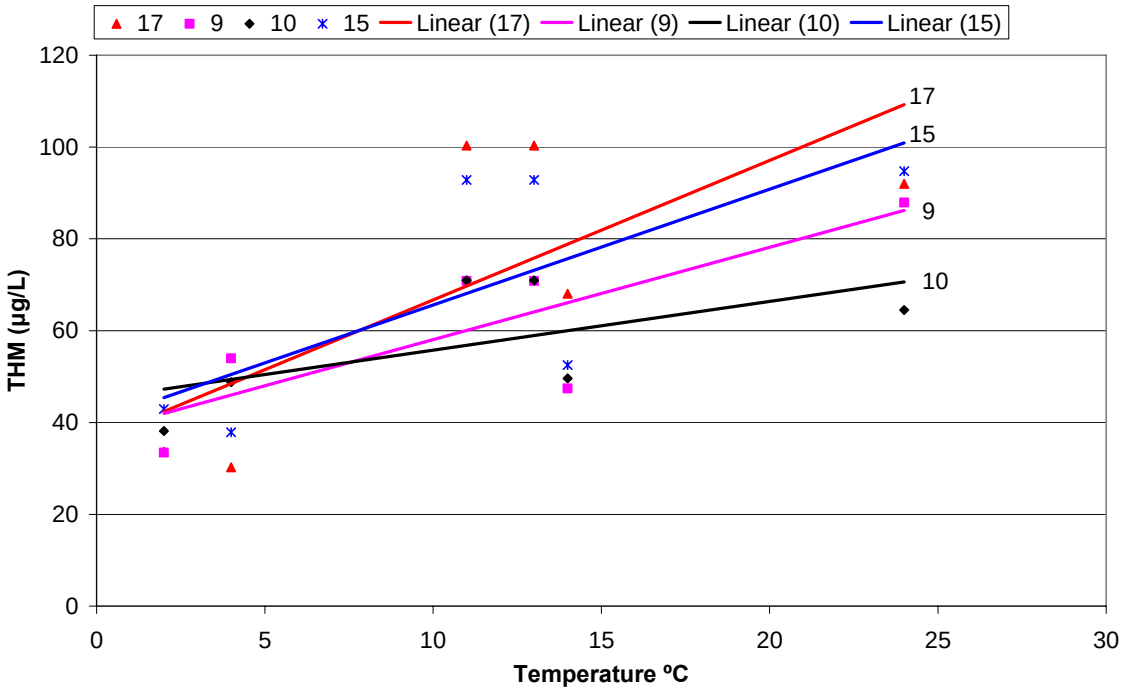

Figure 6. THMs versus Temperature in Randall Community Water District, a system using free chlorine. Numeric values 17, 9, 10, and 15 represent different sample locations.

free chlorine. Generally speaking, each of the four locations in Figure 6 exhibits higher DBP values with increasing temperature. Specifically, TTHMs are shown in this figure. The average rate of change of

TTHM with respect to temperature (change in TTHM per degree change in temperature) is 0.9 µg/L. HAAs, not shown, exhibited a less pronounced effect but did exhibit higher values in summer than in winter. These patterns were comparable in the other systems using free chlorine as a disinfectant as well.

The temperature effect in the systems utilizing chloramine was less than in the systems using free chlorine. Figure 7 shows the impact of temperature on DBPs for Mid Dakota, a system that uses chloramine as a residual disinfectant.

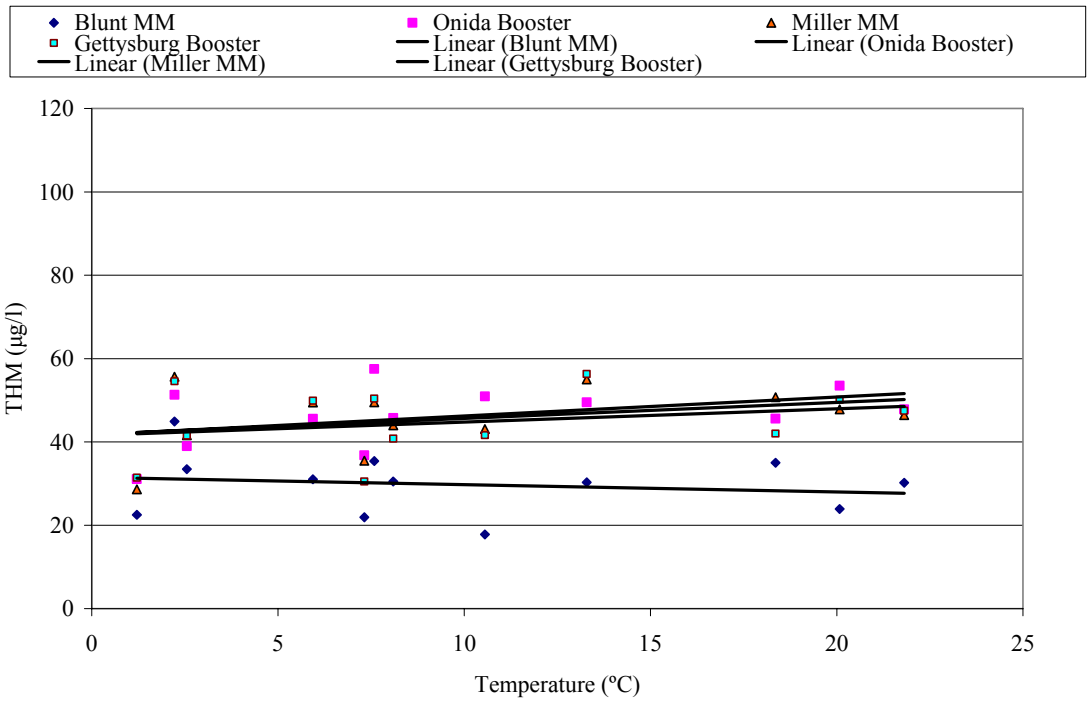

Figure 7. Relationship between the DBP and temperature in chloraminating system (MDRWC). Blunt MM, Onida Booster, Miller MM and Gettysburg Booster are sample locations.

Although the effect of temperature appears not as strong as in the systems using free chlorine, the overall trends in the systems using chloramine nonetheless exhibit increasing DBP concentrations with increasing temperature. The average rate of change of TTHM with respect to temperature (change in TTHM per degree change in temperature) was found to be 0.2 µg/L.

Figure 8 illustrates TTHM behavior in the city of Sioux Falls prior and after the switch to chloramination. From Figure 8, one can see that the concentration as well as rate of change of TTHM is higher in warmer months (May through Aug.) compared to colder months (Nov. through Feb.) supporting earlier stated conclusions. The temperature effect is generally present whether free chlorine or chloramine is used.

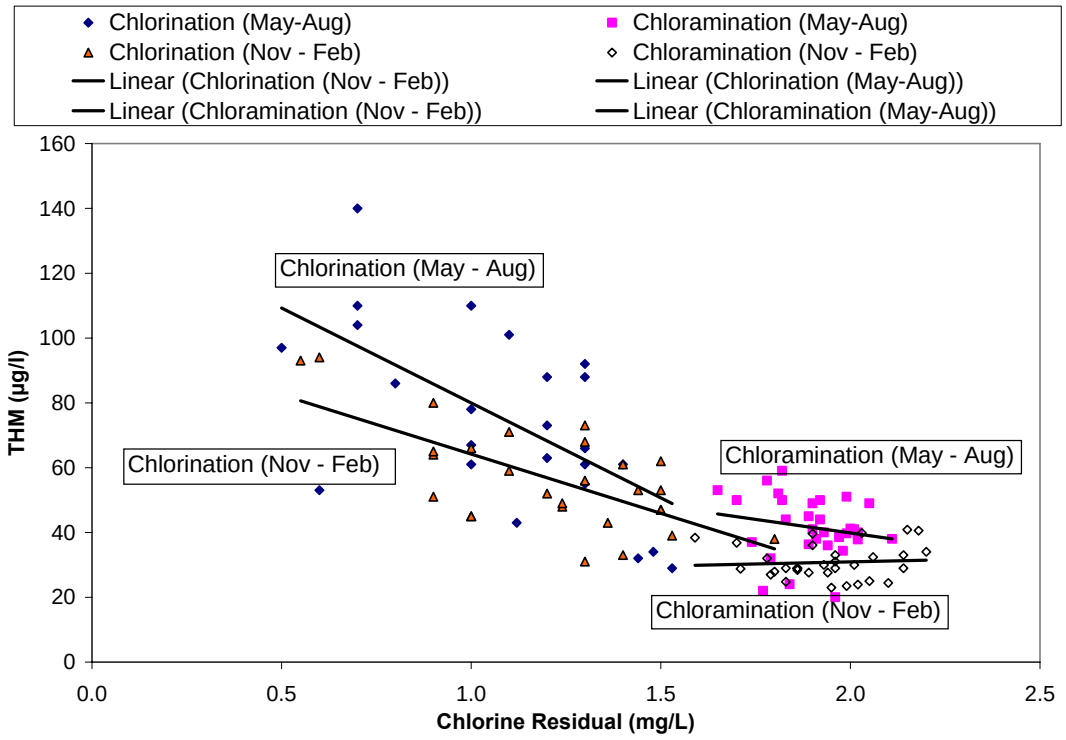

Figure 8. Temperature effect on THM in Sioux Falls distribution system. (May–Aug. represents the warmer months and the Nov.– Feb. represents the colder months.)

It is important to consider the comparative impact that this factor had on DBP formation observed in this research. In all the systems that used surface water or blended surface/ground water sources, peak DBP concentrations occurred in the warmest months. As stated previously, surface waters generally experience greater temperature fluctuation and degrees of water quality variation than do ground waters. This, in turn, effects DBP formation. Generally, higher DBP values are expected during the summer months. This can also be seen in Figure 4 shown previously.

The trend of increased DBP formation with increased temperature may not be true in ground water systems (that exhibit minimal temperature change throughout the year). This is illustrated in Figure 9, showing the variation in DBPs, specifically THM concentration measured at two sites in Brookings, SD from January 2004 to December 2005. Brookings water distribution utilizes groundwater as its water source.

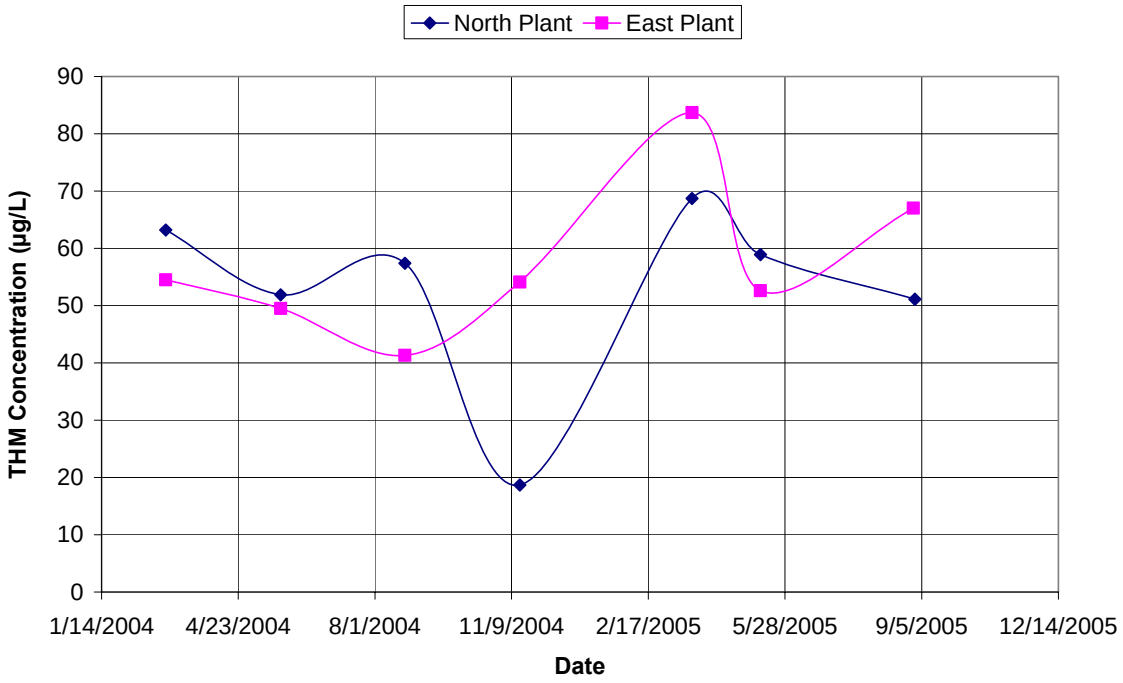

Figure 9. THM concentration in the Brookings distribution system from 2004 to 2005.

As shown in Figure 9, maximum THM concentrations occurred during the cold season. The likely reason for this behavior is the fairly constant temperature of ground water. Since much less water is used in the winter than summer, the water age in the system is much longer in the winter, yielding longer reaction times to form THMs. Because of this, water age predominates over temperature as a major factor effecting DBP formation, and DBP concentrations increase in the winter.

Water Age As water age increases, the reaction time between DBPs and NOM naturally present in water increases. If water age models have not been developed from existing hydraulic models, water age in a distribution system can be approximated from factors such as distance and flow. Typically, water ages increase with decreasing flow (demand) and with distance from the treatment plant. Other factors that can increase water age include storage tank operations and pipe network configuration. These factors were not studied for this project but can have a marked effect on water age and thus DBP formation. Figure 10 and Figure 11 illustrate two of the factors that can be attributed to water age and thus DBP formation.

Figure 10 compares flow versus DBPs, specifically TTHMs for the city of Sioux Falls during chloramination from 2001 to 2005. As flow increases, DBP concentrations increase, indicating another factor affecting DBP formation. The relationship between flow and DBP concentrations illustrated in Figure 10 are opposite what might be expected. This apparent contradiction is most likely due to temperature variations. Temperature was observed to play a greater role in DBP formation than water age for the four surface water systems examined in this study.

Distance from the treatment plant also affects water age. This is a factor that could have an effect on wholesaler and consecutive systems that must transport water over great distances for water use. Figure 11 consists of one of the wholesale South Dakota systems studied and a variety of consecutive systems. This system utilizes free chlorine as a secondary disinfectant.

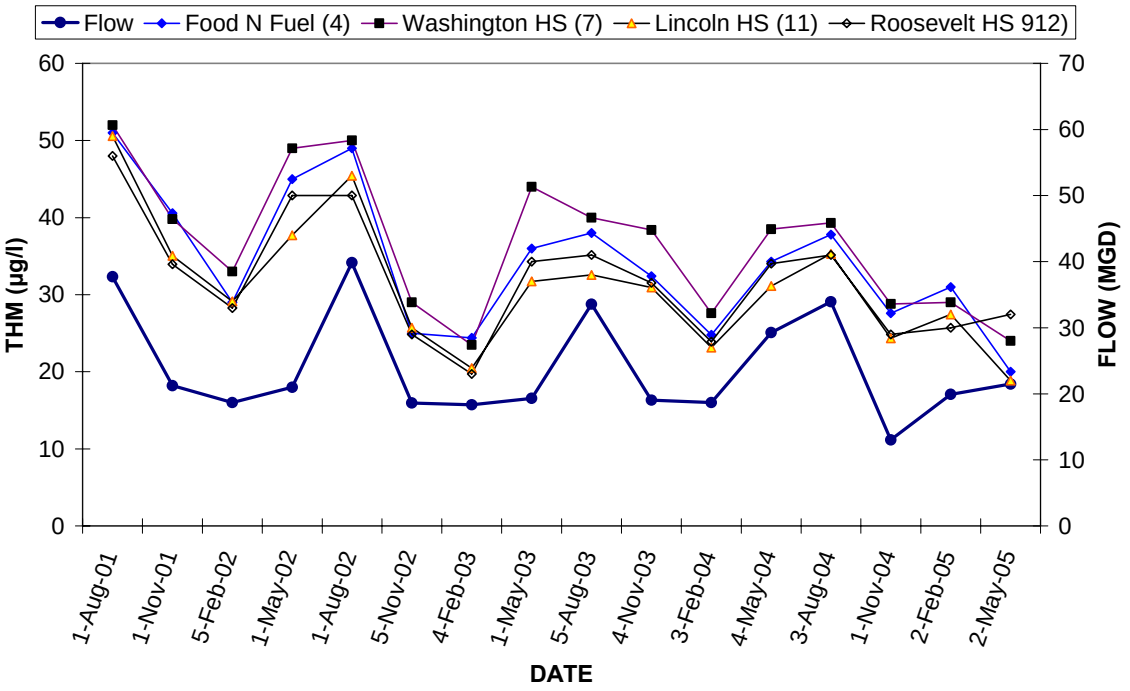

Figure 10. Variation of flow and THM from Feb. 1998 to May 2001 for Sioux Falls, SD. (during chloramination)

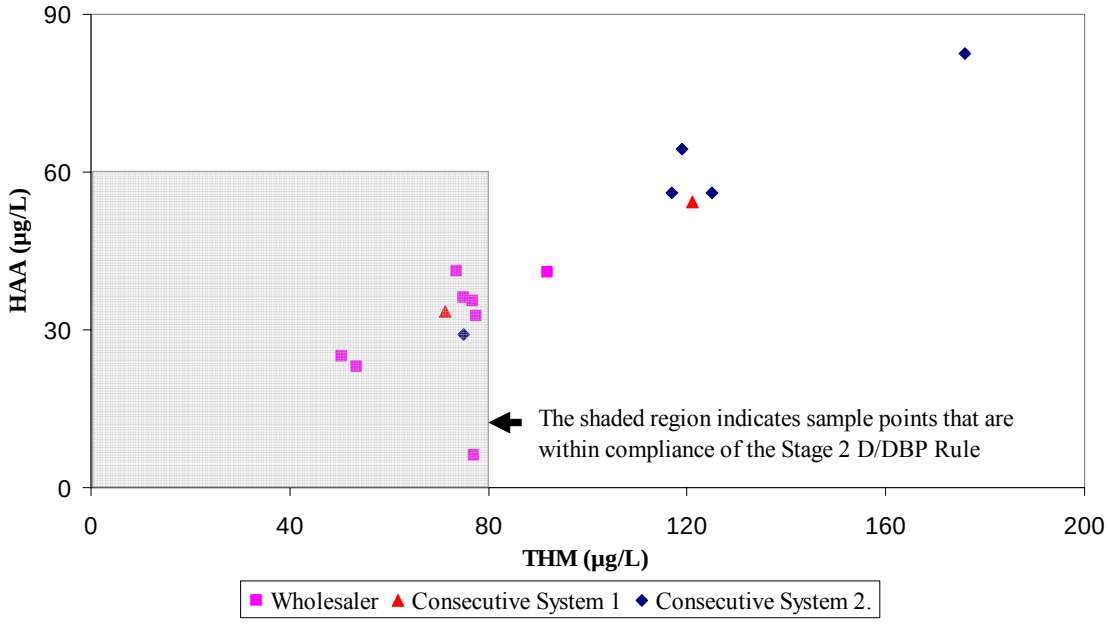

Figure 11. DBP's in Consecutive Systems in which the Wholesaler Boosts Free Chlorine Residual

As observed in the right-hand side of Figure 11, DBP formation has continued to increase throughout as the water moved from the wholesaler to the consecutive system. In this case, unless measures are taken, the two consecutive systems may be out of compliance for the Stage 2 D/DBP Rule. In this system, the chlorine residual was boosted at the location where the water passed from the wholesaler to the consecutive system. The chlorine levels maintained in this system supported both THM and HAA production.

TTHM and HAA5 Behavior Other than the Watertown Lake Plant distribution system mentioned above, THM and HAA5 concentrations both increased with water age in the distribution systems examined in this study. One potential reason for this is that the disinfectant residual maintained in the distribution systems are typically greater than 1.5 mg/L for systems using free chlorine and greater than 2.0 mg/L for systems using chloramine. Figure 12 shows the THM and HAA5 relationship in Sioux Falls, SD when free chlorine was utilized.

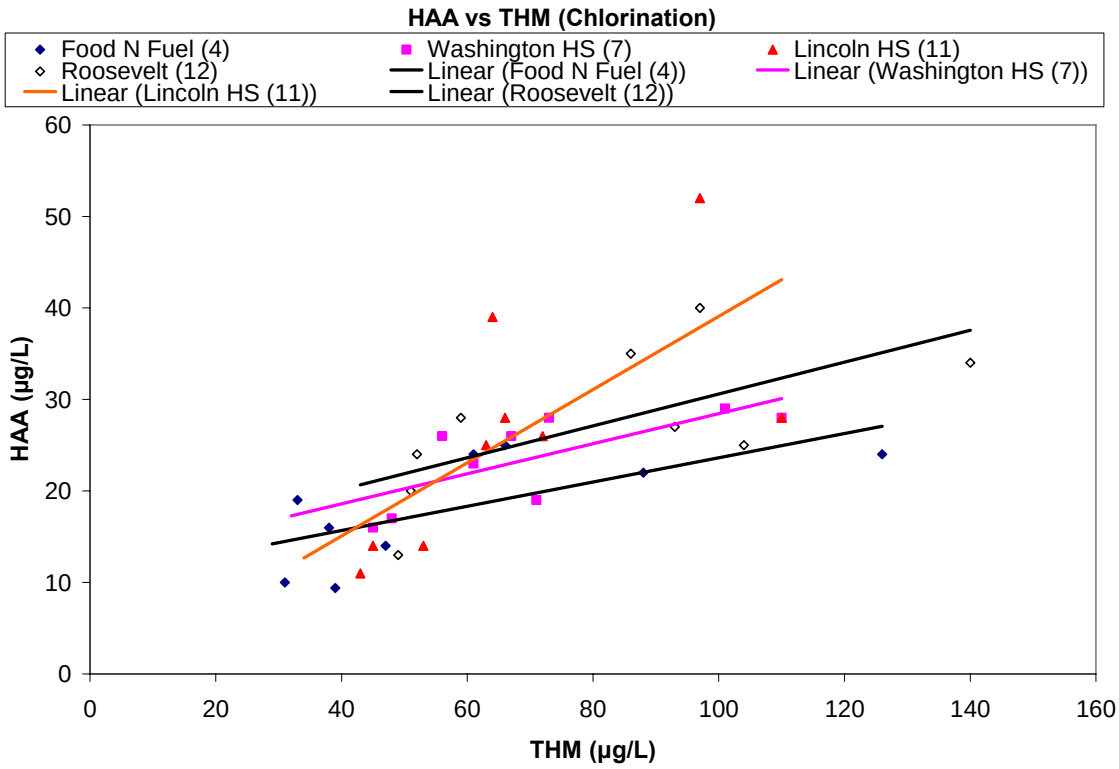

Figure 12. Relationship between HAA5 and THMs in Sioux Falls, SD, during the use of free chlorine as a secondary disinfectant. Numbers 4,7,11 and 12 are sample locations.

The approximate correlations shown in Figure 12 reveal that for every 1 µg/L THM formed, 0.13 to 0.4 units of HAA5 were formed. Similarly, for RCWD (not shown), for every 1 µg/l of TTHM formed, an average of 0.2 µg/l of HAA5 were formed. This would suggest that the rate of TTHM formation was higher in than HAA5 formation in the distribution system. Also, the difference in slopes shows the irregularity and the sensitivity of THM and HAA5 formation to the other factors such as water age and temperature. Figure 13 illustrates TTHM versus HAA5 formation for Sioux Falls, SD after the switch to

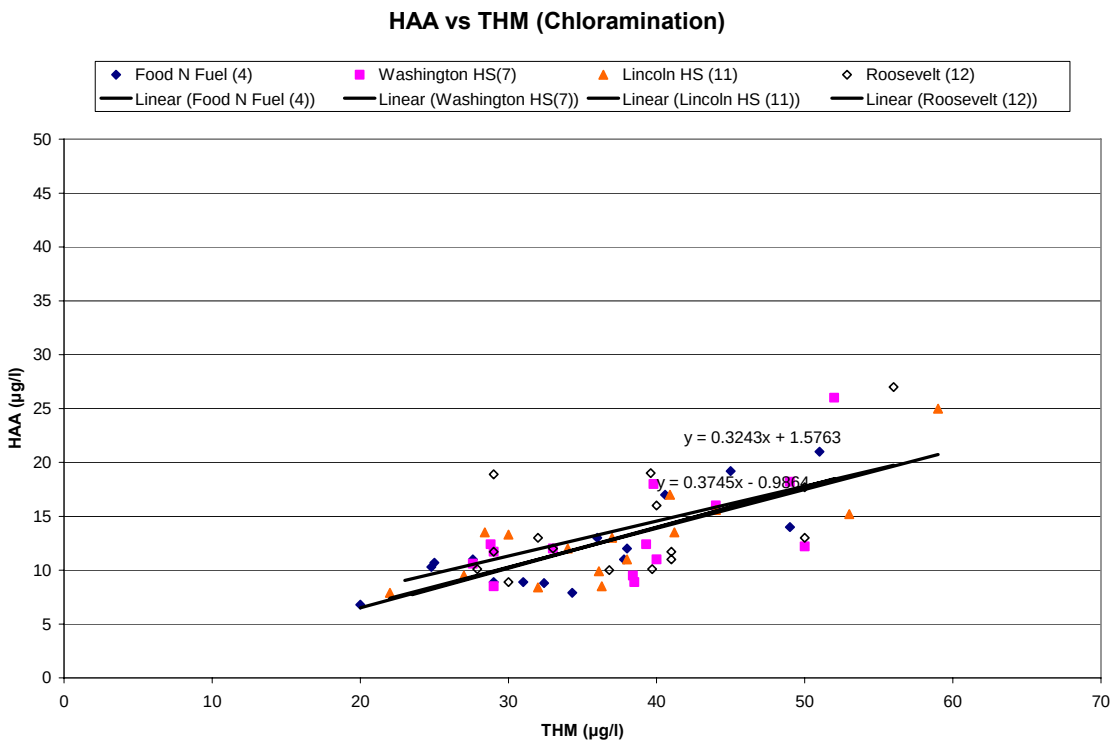

Figure 13. Relationship between HAA5 and THMs in Sioux Falls, SD, after the start of chloramination. Numbers 4,7,11 and 12 are sample locations.

chloramination. These data are more closely bunched together, indicating less variation between THM and HAA5 across the distribution system.

Other Factors Studies have shown that the main factors that typically influence DBP formation include disinfectant type, disinfectant dose, source water quality and bromide content, temperature, water age, pH, pipe type and wall environment, and distribution system layout (Adams et al. 2005, Carlson and Hardy 1998, Clark and Sivaganesan 1998, EPA 2003, Liang and Singer 2003). Factors not extensively studied in this research project either because the factors were held relatively constant and thus would not contribute to DBP concentration and disinfectant residual variations, or they were not factors that South Dakota water distribution systems could easily use to predict peak THM and HAA5 locations for their IDSE include:

- **Source water quality:** The most significant source water quality parameter affecting DBP formation is the NOM content and type. NOM can be divided into a hydrophobic or hydrophilic carbon type. Hydrophobic carbon contributes to DBP formation more than the hydrophilic portion; however, the hydrophobic is also the portion that is most readily removed by enhanced coagulation with alum or ferric chloride (Liang and Singer 2003).
- **pH:** pH affects the rate of DBP formation. THMs formation rates have been found to increase as pH increases above 8 while HAA5 formation rates have been found to increase at a lower pH of 6 (Diehl et al. 2000, Liang and Singer 2003).
- **Pipe type**: Pipe type and the corresponding wall environment can affect DBP formation by affecting the disinfectant residual through reactions at the pipe wall (Hallam et al. 2002). The

rural water systems studied in this project were comprised almost entirely of PVC pipe which is a considered a relatively non-reactive pipe that would not impact chlorine residual. The municipal systems both contain older distribution system sections that have sections that are not PVC and are most likely lined iron pipe. However, some unlined iron pipe might also be present. These areas could have influence DBP formation by exerting a chlorine demand at the pipe wall.

- **Pipe environment**: Biofilm can have a pronounced effect on DBP formation, specifically HAA5 formation. Chen and Weisel found that as THMs continued to increase in distribution systems, HAA5s were found to increase and than decrease. Speight and Singer noticed the same phenomena. This occurs where biofilms are present, and biofilms typically grow at low disinfectant residuals. There were no strong trends that exemplified these phenomena in any of the distribution systems that were analyzed most likely due to high enough residuals that prevent biofilm growth in the distribution systems.
- **System Layout**: The distribution systems analyzed consisted of two municipal or looped systems and two rural or branched systems. All had storage tanks. These characteristics directly relate to water age. Looped systems are designed to minimize distribution system dead ends that could increase water age substantially. Branched systems in comparison are used primarily for transport of water over long distances. Storage facilities store and thus age water especially if the storage system has the possibility of stagnation due to lack of movement. All of these characteristics can affect DBP formation because of the effect they have on water age. Thus, the system layout affects DBP production directly through water age.

Principal Findings and Significance

The following relationships were observed from data collected at the 4 water distribution systems that were in studied South Dakota.

- Chlorine residuals can be used as an indicator of THM formation – the lower the chlorine residual, the greater the THM concentration.
- Systems using free chlorine as a secondary disinfectant exhibited higher DBP formation than systems utilizing chloramine.
- Systems using free chlorine will likely find chlorine residuals a useful tool for identifying areas of high DBP concentrations for the maximum DBP sample site required by the Stage 2 DBP rule. However, systems using chloramine residuals will likely have less success identifying high DBP concentrations using disinfectant residual concentration because of the quenching effect of chloramine on DBP formation. For these systems, water age will likely be the best indicator of DBP formation.
- When the chlorine residual in the distribution system is held above 0.5 mg/L, chlorine residuals can also be used as an indicator of HAA5 formation – the lower the chlorine residual, the greater the HAA concentration. When the chlorine concentration falls below 0.5 mg/L, HAA5 concentrations may drop, likely due to microbial degredation.
- When surface water is used as the water source, DBP concentrations increase with increased treated water temperature. However, due to lack of temperature variation, ground water systems exhibiting significant DBP formation may experience highest DBP formation in the winter, when water age is the longest.
- When the chlorine residual in the distribution system is held above 0.5 mg/L, TTHM and HAA5 concentrations increase with water age in the distribution system. The rate if increase is greater when using free chlorine as the final disinfectant as compared to using chloramine as the final disinfectant.
- In the presence of substantial free chlorine residual, TTHM and HAA5 concentrations continued to increase in consecutive distribution systems, potentially to concentrations exceeding the MCLs.

These findings will enhance the ability of regulators and systems to meet the requirements of the

Stage 2 D/DBP rule. Consecutive systems who have not yet gathered D/DBP data are encouraged to obtain early samples to be able coordinate compliance efforts with the wholesale system.

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PART II:

Information Transfer Program:

The results of this study were to be communicated to engineers, operators and managers of water supply systems through presentations at conferences. Thus far, the results have been communicated through presentations at 4 conferences and with poster presentations at 2 events.

Student Support:

Two graduate students studying in the Civil and Environmental Engineering Department, Morgan Gagliano and Akshaya Niraula, were supported by this research project. They have used the data in preparation of their MS in Engineering thesis. They expect to graduate in the Summer/Fall 2006 term.

Publications/Presentations:

Presentations:

Delvin E. DeBoer. "SDSU Water Research: DBPs, Membrane Concentrate, Mixing." Presented at the 71th Annual Conference of the South Dakota Water and Wastewater Association, Brookings, SD, September 15, 2005.

Delvin E. DeBoer. "Fate of DBPs in the Distribution System: Preparing for the IDSE." Minnesota Section of AWWA 89th Annual Conference – Duluth, MN, October 6 2005.

Akshaya Niraula and Delvin E. DeBoer. "Fate of DBPs in the Distribution System: Preparing for the IDSE." South Dakota Water and Wastewater Association Water Operators Seminar, Sioux Falls, SD, February 8, 2006.

Delvin E. DeBoer. "Fate of Disinfectants and DBPs in Water Distribution Systems." 18th Annual Environmental and Ground Water Quality Conference, Pierre, SD, March 16, 2006.

Poster Presentations:

Morgan Gagliano. "Fate of Disinfectants and Disinfectant Byproducts in Water Distribution Systems." South Dakota Board of Regents Research Day at the Capital, Pierre, SD, February 8, 2006.

Morgan Gagliano and Akshaya Niraula. "Fate of Disinfectants and Disinfectant Byproducts in Water Distribution Systems." Surface Water Treatment Workshop, ND/MN/SD Sections of AWWA, Fargo, ND, April 26, 2006.